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Indoor air quality investigation before and after relocation to WELL-certified office buildings

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ABSTRACT

Air pollutant exposure in workplace environments has been associated with health and cognitive outcomes of workers. While green building certification programs have been instrumental in promoting indoor air quality (IAQ), the present literature indicates inconsistent evidence. Recent emergence and proliferation of WELL certification program that prioritizes human health has evoked new questions about its effectiveness in relation to IAQ. To investigate the effectiveness of the WELL certification, we have quantitatively compared IAQ results before and after relocation to two WELL-certified office buildings using the same cohort of occupants. Physical measures included integrated samples of TVOC, individual VOC, formaldehyde and acetaldehyde, NO_2, SO_2, O_3 and longitudinal records of CO_2 and size-resolved particles. Complementary survey responses about satisfaction with IAQ and thermal comfort were collected from ~250 employees. For the majority of air pollutants, there was no significant concentration difference between non-WELL and WELL buildings, but not always. The WELL-certified buildings had substantially higher levels of TVOC and individual VOC associated with paints, especially shortly after the relocation. However, there was statistically significant improvement in IAQ satisfaction after relocation into WELL buildings regardless of the air pollution levels, possibly confounded by thermal environment, awareness of the WELL certification or other non-measurable factors.

1. Introduction

Since the appearance of the first green-certified buildings in the 1990s, their performance targets have been evolving. While the green building industry has a long-standing history of attention to human health, its core objectives prioritized mitigation of environmental impact by reducing energy and water use, waste production and site disturbance. More recently, we have witnessed a shift in the prioritization of objectives relative to the others, with a stronger emphasis on building characteristics that explicitly promote the experience of building occupants. This came as a result of several decades of research and industry insights on adverse implications of poor indoor environments on well-being and that more effective interventions were possible. For instance, energy conservation measures such as tightening the building envelope to reduce uncontrolled outdoor air infiltration [1,2], have led to impaired perception of air quality and increased incidence of building related subclinical health symptoms — also known as *Sick Building Syndrome* (SBS) symptoms [3,4]. These can vary from mild symptoms (e.g. headache, shortness of breath, fatigue, eye and throat irritation) to acute incidents, such as carbon dioxide poisoning [5] and Legionnaire's disease [6].

Air pollutant exposures indoors and occupant satisfaction with the quality of indoor air are not only associated to health outcomes, but also to overall human well-being, cognitive performance and learning [7–12]. In workplace environments particularly, this comes with enormous economic implications [13], as the costs of office employees are estimated to be two orders of magnitude higher than operating costs associated with building energy use [14,15]. This offers a compelling case for the building industry as reflected in the recent emergence of green building certification schemes that prioritize human health. However, while the benefits related to energy and water savings are relatively well-documented [16], the IAQ and occupant satisfaction in green buildings are only recently being studied [17].

Majority of research examining the performance of green-certified buildings in relation to IAQ and occupant satisfaction stem either from green-certified buildings alone, or from comparative studies between

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green-certified and conventional buildings. In spite of the general understanding that green-certified office buildings result in better IAQ and occupant satisfaction [18], reviews of the recent literature indicate an equivocal nature of the findings [19]. While multiple studies found that green-certified office buildings contribute to improved perception of IAQ relative to conventional offices [20–25], others reported matching [26–29] or even lower satisfaction levels [30,31]. Except a few notable studies [24,32–34], a common attribute of available research is that a very few included direct comparison of subjective measures before and after relocation to a green-certified building with a same cohort of occupants. Because humans are different (age, gender, job responsibilities, etc.) and organizational structures differ from one company to another, it is important to control for confounding factors. This can be achieved by having comparison groups which are based on the same occupancy cohorts.

Another common attribute is that the majority of IAQ-related studies in green-certified buildings are based on self-reported and subjective measures on IAQ from post occupancy surveys only. Relatively few studies in green-certified buildings performed physical measurements of IAQ or even less a combination of both physical and subjective investigations. Among a handful of studies including physical measurements of IAQ, they focused on air pollutants such as carbon dioxide [21,23,35–38], carbon monoxide [21,36,39], total or individual volatile organic compounds (VOC) [23,35,36,39,40] ozone [39], particulate matter [21,35,36,39], and biological samples of bacteria and fungi [36,39]. Many of these studies are short-term and lack longitudinal assessment over multiple seasons. In addition, the subjective results of IAQ assessment are rarely connected to the physical and chemical measurements [17,41]. Notably, none of the existing studies directly compared IAQ performance between two different green-certification schemes based on occupancy transitioning from one to another green-certified building.

Along the above mentioned knowledge gaps, it is important to recognize the recent emergence and rapid adoption of several green certification schemes that prioritize occupant health [e.g., 42,43. In this context, the WELL v2 certification is the most rapidly growing green rating system worldwide that aims to promote health-based building design and operation [42]. The WELL certification encompasses ten health-relevant concepts, four of which relate to measurable indoor environmental quality (Air, Light, Thermal Comfort and Sound). The Air concept has four requirements: 1) meeting specific thresholds for particulate matter ($PM_{2.5}$ and PM_{10}), organic gases (benzene, formaldehyde, toluene and TVOC (Total Volatile Organic Compounds)) and inorganic gases (carbon monoxide and ozone), 2) provision of smoke-free environment, 3) meeting requirements of conventional building ventilation standards, and 4) managing air pollution during building construction and renovation. Other strategies that lead to further indoor air quality enhancement are optional (e.g., more stringent threshold for indoor air pollutants (including nitrogen dioxide and a broader suite of VOC), enhanced ventilation based on low CO_2 levels, enhanced filtration, air quality monitoring, source separation, adoption of materials that reduce hazardous VOC and SVOC emissions, relative humidity control, etc.). Pursuing these optional strategies is needed to achieve higher levels of certification, such as Silver, Gold or Platinum. Another important feature of the WELL v2 certification is the need for recertification every three years to assure continuous performance of buildings.

To date, no studies have investigated the success of WELL-certification program relative to other green-certified and conventional buildings. Specifically, it is not known whether WELL-certified buildings lead to improved IAQ relative to other buildings. This study is the first that contributes to bridging this knowledge gap by quantitatively comparing physical and subjective IAQ measures before and after relocation to two WELL-certified office buildings using the same cohorts of occupants. The primary objective of this study is to assess physical and subjective IAQ parameters in the two office buildings before relocation (from BREEAM-certified and conventional), and to quantitatively compare the results after the relocation to the two WELL-certified office buildings using the same cohort of occupants. In this study, we also seek to understand the effect of source contribution and seasonal variations on physical and subjective IAQ assessment, as well as possible confounding influences of thermal environment.

2. Methods

2.1. Study sites

Two office building pairs located in one of the large cities in the Netherlands were selected as study sites (in total four buildings). The selection criteria included the following: a) that a company of each building plans to relocate into a WELL certified building during 2019; b) that company has minimum of 50 workers to achieve sufficient statistical power for subjective data; and c) that building managers are willing to take part in the study and facilitate its execution.

Out of two companies that fulfilled this criteria, Company A already had BREEAM certification before the relocation while Company B was a conventional non-certified building. Distance between the pre- and post-relocation buildings was relatively low (2.3 km for Company A; 6.7 km for Company B). Therefore, differences in terms of the level of urbanization and outdoor climate were small; the latter was confirmed by the outdoor climate measurements performed throughout the campaign (Table S1). Company A counted a much higher number of employees (here referred to occupants) and their number increased to 500 by the end of the study. Company B had a stable number of occupants (70). All buildings were mechanically ventilated with 100% outdoor air, designed in accordance with local Dutch standard NEN 1087. Table 1 summarizes key characteristics of the selected case study buildings.

2.2. Field campaign design

The study consisted of three 4-weeks long measurement campaigns per company (in total 6 campaigns): 1) within 3 months before relocation, 2) within 3 months after the relocation, and 3) after additional 7–8 months from the second campaign (Fig. 1). The purpose of the additional measurement campaign during the post-relocation phase was to probe the time effect after moving into a new/renovated office building on physical and subjective IAQ assessment. All campaigns fell into winter and summer seasons. The last measurement campaign for Company B was delayed by three months as a result of work-from-home requirement during Covid-19 pandemic. The occupants returned to their office in August 2020, and the campaign was executed one month later.

The air temperature, relative humidity, carbon dioxide (CO_2) and size resolved particle number concentration (0.3–10 μm) were continuously monitored and recorded during the field campaigns. The longitudinal measurements continued for four consecutive weeks. Additional integrated samples were used to collect information about levels of TVOC and selected individual VOC, formaldehyde and acetaldehyde, sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3). These air pollutants are known to be commonly present in office spaces [44,45]. Except SO_2 and certain VOCs, majority of measured parameters are incorporated into the WELL v2 certification. Duration of integrated sample collection was limited to seven days, and it was always scheduled in the first week of a campaign.

In each campaign, there were at least four measurement and sampling locations: open space office, meeting room, private office and outdoors. The three indoor locations contained the full suite of air quality devices and samplers. The measuring devices and samplers were normally positioned at the workstation around the breathing zone height, within 1.0–1.2 m height above the floor. They were also placed at least 1.5 m away from the breathing zone, doors, walls, windows and ventilation diffusers. Not positioning the monitors and samplers directly in the breathing zone could lead to underestimation of true inhalation

Table 1
Characteristics of building pairs selected as case studies.

	Company A	Company A	Company B	Company B
	Pre-relocation	Post-relocation	Pre-relocation	Post-relocation
Certification	BREEAM-NL	WELL v2	None	WELL v2 BREEAM-NL
Certification level/ type	BREEAM Asset "Very Good"; Building Management "Good"	WELL Platinum/ Core&Shell	–	WELL Platinum/Core&Shell; BREEAM Excellent/New Construction
Construction year	2009	1960	1950	2020
Renovation year	None	2020	2002	None
No of employees	464	500	70	70
No of workstations	288	309	64	84
Mechanical ventilation	100% filtered outdoor air	100% filtered outdoor air	100% filtered outdoor air	100% filtered outdoor air
Ventilation operation	Mon-Fri 7:00–19:00h; 50% rest of the time	Mon-Fri 7:00–19:00h; 50% rest of the time	Mon-Fri 7:00–20:00h; 50% rest of the time	Mon-Fri 6:00–19:00h; 50% rest of the time
Heating/Cooling	Fan-coil	Fan-coil	Fan-coil	Radiant ceiling
Area (m^2)	4223	4361	1210	1220

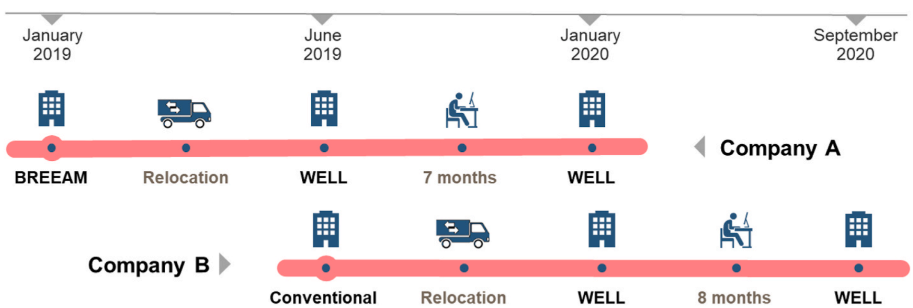

Fig. 1. Stages of the field campaigns with the associated timelines.

exposures associated with particles [46] and CO_2 [47]. Additional continuous measurements of CO_2, air temperature and relative humidity were taken in the hallways and kitchens. Outdoors, we measured only NO_2, SO_2 and O_3 in addition to air temperature and relative humidity. The outdoor monitoring kit was positioned on the building façade of the first floor of the building, at least 3 m above the ground level.

2.3. Experimental equipment and sampling

The measurements of CO_2 and particle number concentration were taken with 5-min resolution to record unsteady responses to dynamically changing conditions typically encountered in office buildings. Table 2 summarizes the information of measured air pollutants, measurement methods, instrument models, technical and analysis specifications.

IVL (Swedish Environmental Research Institute) diffusive samplers [48] were used for measurements of concentrations of NO_2, SO_2 and O_3. The samplers are cylinders with a diameter of 25 mm and height of 13 mm. The sampling technique is based on molecular diffusion. The compounds are quantitatively collected on an impregnated membrane during a period of time. For measurements of TVOC (including individual VOC), formaldehyde and acetaldehyde, selective diffusive devices were used (Table 2).

2.4. Questionnaire surveys

In addition to physical measurements, a web-based survey questionnaire was administered to building occupants during each campaign (three per company, six in total; see Fig. 1). Each survey remained open for three weeks and the building management sent two follow up emails in order to augment the response rate. The results reported in this study are part of a more comprehensive survey study that aimed to evaluate the perceived occupant satisfaction with indoor environmental quality (including lighting, acoustic, cleanliness, maintenance, office furnishings and layout and overall workplace satisfaction) [51,52], self-assessed productivity and sick building syndrome symptoms. Here, we focused on questions relating to IAQ and temperature satisfaction before and after the relocation along with potential sources of dissatisfaction.

Table 2
Summary of monitored air pollutants and sampling/analysis methods.

Air pollutant	Method	Manufacturer/ Laboratory
Particulate matter resolved particle number concentration in six size bins: 0.3–0.5; 0.5–1; 1–2.5; 2.5–5; 5–10	optical particle counter that sizes particles based on light scattering	1) Met One HHPC 6+, Beckman Coulter Life Sciences, IL, USA 2) GrayWolf PC-3500, GrayWolf Sensing Solutions, CT, USA
Carbon dioxide (CO_2) also includes air temperature and relative humidity records	non-dispersive infrared self-calibrating CO_2 sensor with reported accuracy of ±50 ppm and ±5% of reading	HOBO MX CO_2 Data Logger, Onset Computer Corporation, MA, USA
TVOC (n = 20 individual VOC) Individual VOC are presented in Table 4	diffusive sampling on Tenax TA adsorbent tubes. In compliance with ISO 16017–2 [49]	Markes International, Llantrisant, UK
Aldehydes (n = 2) Formaldehyde, acetaldehyde	diffusive sampling on DSD-DNPH Aldehyde Diffusive Sampling Device. In compliance with ISO 16000–4 [50]	Suppelco, Bellefonte, PA, USA
Nitrogen dioxide (NO_2)	Diffusive sampling	IVL diffusive sampler
Sulphur dioxide (SO_2)	Diffusive sampling	IVL diffusive sampler
Ozone (O_3)	Diffusive sampling	IVL diffusive sampler

The satisfaction questions were answered by means of standardized 7-point scale ranging from "very dissatisfied" (−3) to "very satisfied" (+3), with a neutral midpoint (0). Answers marked with "dissatisfied" prompted more thorough follow up questions to gain insights into sources of dissatisfaction with IAQ and thermal comfort.

The collected response rate varied between 31 and 44% across all six campaigns. In Company A, we collected responses from 202 occupants before relocation, followed by 203 and 253 responses after relocation to the WELL-certified building. In Company B, we collected responses from 53 respondents in the conventional building (pre-relocation), and subsequently 36 and 39 responses in the WELL-certified building (post-relocation).

2.5. Data analyses and statistical methods

The continuous data were processed in a way to retain only working hours (08:30–20:30h) while excluding weekends and public holidays. The assumption of the 12 h occupancy therefore represents the lower-bound estimate of the physical IAQ data because the majority of employees are present during 9 h only. The PM_{10} and $PM_{2.5}$ mass levels were computed by summing estimated particle mass concentrations in the size bins between 0.3 and 2.5 μm, and between 0.3 and 10 μm, respectively. Contribution of particles with optical diameter <0.3 μm (below the instruments' detection limits) to particle mass concentration were considered negligible as the particle mass tends to increase with particle size as it scales to diameter cubed [53]. Concentrations of particles smaller than 0.3 μm should however be investigated in the future owing to potential risks resulting from elevated exposures [54]. For particle number to mass conversion, we assumed that: (i) particles are spherical; (ii) particle density is 1 g/cm^3 – the water density which should be considered as lower-bound estimate relative to typical indoor particle density range of 1–2.5 g/cm^3 [55,56]; and (iii) the mass-weighted particle size distribution is constant in each size bin [57].

NO_2, SO_2 and ozone were analyzed by wet chemical techniques using a spectrophotometric method (NO_2) and ion chromatography (SO_2 and O_3). The VOC sampled on the Tenax tubes were thermally desorbed (Markes International, Unity 1 and Ultra, during 5 min at 250 °C) and analyzed by gas chromatography/mass spectrometry (GC/MS). The gas chromatograph (GC) was an Agilent 6890 equipped with a mass selective (MS) detector (Agilent 5973 N) in electron impact mode for compound identification. The GC was equipped with a CP Wax 52C (Agilent) capillary column (Polyethylene glycol phase, 60 m, 0.32 mm i. d., 1.2 mm film thickness) and used helium as carrier gas. The GC oven temperature program was started at 50 °C and increased to 100 °C at 4 °C/min. then increased to 220 °C at 8 °C/min. and maintained for 10 min. TVOC was quantified using the uptake rate and the response factor of toluene. Ten individual VOC were quantified specifically using their compound specific uptake rates and response factors: limonene, a-pinene, 3-carene, benzene, toluene, m-xylene, hexanal, 1-butanol and 2-ethyl-1- hexanol. The other individual VOC were quantified in toluene equivalents. Calibration was achieved by application of microliter amounts of solution of the compounds in methanol on Tenax tubes.

For the purpose of direct comparison of before-and-after responses from the questionnaire surveys, we removed the votes of "newcomers" (new employees) in the post-relocation phase (Company B did not have newcomers). The mean and median values of satisfaction with IAQ and temperature parameters were computed by averaging satisfaction votes of each occupant in the two buildings. The statistical significance was tested by the Wilcoxon rank sum test, also known as Mann-Whitney test. This is an alternative to *t*-test and computes p-value. Because the p value can be influenced by the size of the effect, we also computed Spearman's rho that varies between −1 and +1, where 0 indicates no association. In sum, the statistical significance was considered when the p value was below 0.05, and when the effect size (Spearman's rho) was above 0.2 [58].

2.6. Quality assurance

For accurate comparison of results recorded with multiple CO_2 monitors and two brands of optical particle counters (Table 2), we performed data correction using adjustment factors derived from multiple side-by-side tests of instrument performance through the campaign (Table S2). Flow rate checks for particle counters were conducted at the beginning and the end of the measurement campaigns and all the results were always within the 4% range reported by the manufacturers (2.83 L/min). The performance of CO_2 monitors was within manufacturer-specified values. Adjustment of CO_2 values was not needed as the relative differences were always below 3% considering the range between 400 and 1000 ppm.

The analytical procedures for the inorganic air pollutants are accredited by the Swedish accreditation agency SWEDAC. The limit of detection (LOD) was 0.7 μg/m^3 for SO_2 and NO_2 and 7 μg/m^3 for ozone. The measurement uncertainty was, at 95% confidence level, 12% for SO_2 and 10% for NO_2 and ozone. The procedures for the determination of TVOC and the aldehydes followed IVL's internal methods, based on the ISO standards. The LODs for individual VOC, formaldehyde and acetaldehyde were 0.1 μg/m^3, 0.06 μg/m^3 and 0.3 μg/m^3, respectively, based on 3 times the signal-to-noise ratio and 7-days sampling period. The corresponding measurement uncertainties were 10%, 20% and 40% for TVOC, formaldehyde and acetaldehyde, respectively.

3. Results and discussion

3.1. Summary of real-time data

The real-time measurements performed during the occupied hours in the open office, private office, meeting room, and outdoors of the two companies over three campaigns provided more than half a million data points.

Fig. 2 presents box plots of the fundamental indoor climate parameters (air temperature, relative humidity and CO_2) measured in the two companies before and after relocation to the WELL-certified buildings. Because both building pairs were mechanically conditioned yearlong, air temperature, relative humidity and CO_2 levels were generally within the standard limits. Considering air temperatures, both mean and median values in BREEAM and WELL-certified buildings were always between 22 °C and 23 °C. For the same buildings, values of the 5th and 95th percentiles stayed within 21 °C and 24 °C, indicating excellent control of the air temperature. The conventional building of Company B had much higher air temperatures during the summer 2019, which averaged at 24.7 °C. The 95th percentile value was 25.7 °C, indicating that during at least 5% of the occupied hours, the air temperature was near the upper limit of the operative temperature for mechanically conditioned space during the cooling season (26 °C), which falls between the second and the third Standard Categories [59,60]. Even though the Company B had higher indoor air temperature before the relocation, outdoor temperature data before relocation (mean = 22.1 °C) was similar to that after relocation (mean = 21.6 °C) (Table S1), which could indicate insufficient capacity of the cooling system or reduced airtightness of the Company B building before relocation. Table 3 summarizes the mean ± standard deviation, and 95th percentile values for dry-bulb temperature, and other continuously monitored values in the two companies before and after their relocation into the WELL buildings.

The measured relative humidity was generally within the recommended standard limits, but not always. During the winter, relative humidity levels were expectedly lower. Before the relocation, the BREEAM-certified building of Company A had a mean relative humidity of only 29% (5th percentile = 22%; min = 18%). While this mean value complies with the second Category of the Standards [59,60], it is apparent that the humidification system of the HVAC system was not operational. The humidity management in the WELL-certified building

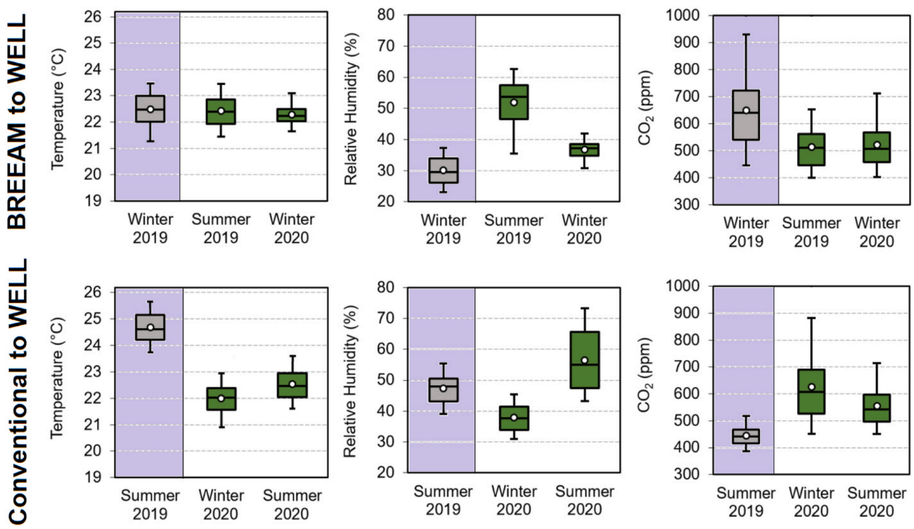

Fig. 2. Boxplots of air temperature, relative humidity and concentrations of CO_2 before and after relocation into the two WELL-certified office buildings. The results are averaged across three measurement locations (open space, private office and meeting room). Shaded purple areas represent pre-relocation conditions, either from BREEAM (Company A) or from conventional building (Company B). The results are obtained based on 5-min mean concentrations. Box plots indicate 1st quartile, mean (while circles), median and 3rd quartile values. The ends of the whiskers represent 5th and 95th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Descriptive data of dry-bulb temperature, relative humidity, CO_2, particle mass below 2.5 μm ($PM_{2.5}$) and particle mass below 10 μm (PM_{10}) levels recorded in the two companies before and after their relocation into WELL buildings.

	T (°C)		RH (%)		CO_2 (ppm)		$PM_{2.5}$ (μg/m^3)		PM_{10} (μg/m^3)	
	mean ± sd	P95	mean ± sd	P95	mean ± sd	P95	mean ± sd	P95	mean ± sd	P95
Company A Winter 2019	22.5 ± 0.7	23.5	29 ± 5	38	650 ± 153	929	3.1 ± 1.9	6.9	15.2 ± 5.8	25.7
Company A Summer 2019	22.4 ± 0.6	23.5	52 ± 8	63	513 ± 84	660	2.2 ± 1.7	4.5	12.2 ± 9.6	24.3
Company A Winter 2020	22.3 ± 0.4	23.0	37 ± 3	42	521 ± 91	710	2.5 ± 1.6	5.8	9.9 ± 5.6	19.9
Company B Summer 2019	24.7 ± 0.6	25.7	47 ± 5	56	445 ± 39	520	2.4 ± 1.8	6.1	8.7 ± 6.2	17.0
Company B Winter 2020	22.0 ± 0.7	23.0	38 ± 5	45	625 ± 130	883	1.9 ± 1.5	4.2	7.3 ± 7.2	11.2
Company B Summer 2020	22.5 ± 0.6	23.7	56 ± 10	73	556 ± 81	710	1.9 ± 1.2	4.3	6.5 ± 3.6	13.4

in winter 2020 was better, averaging at 37%. In Company B, relative humidity before relocation (conventional building) was near the optimal level (mean = 47%) with low fluctuations (interquartile range (IQR) = 8%). One year later (summer 2020), the humidity levels in the WELL-certified buildings averaged at 56% with relatively high oscillations (standard deviation = 10%, IQR = 16%). During 5% of the occupied hours, the relative humidity in the WELL-building was 73% which exceeds even the loosest requirements of EN16798 and ISO 17772 (Category 3 upper limit = 70%) [59,60] and the maximum permissible level of 65% prescribed by ASHRAE [61]. This results also indicates that this building would not meet the requirement of a credit "T07 Humidity Control" of the WELL v2 guideline that specifies that relative humidity must be maintained within 30–60% at all times [42].

The CO_2 levels in both building pairs were within the range typical of properly ventilated buildings [62]. Factors influencing the variability of CO_2 concentrations could be mainly attributed to variable occupancy rates, as the HVAC systems delivered a constant amount of outdoor air. In Company A, relocation from BREEAM to WELL-certified building resulted in lower mean CO_2 levels, from 650 to ~520 ppm. In Company B, relocation from conventional to WELL building increased the mean CO_2 concentrations from 445 to 625 ppm. Considering that number of occupant and office space were kept steady before and after relocation, the reported difference could be attributed to improved airtightness in the building after relocation. Considering 95th percentile values, they were always within the limits of Category 1 (550 ppm above outdoor level) of the Standards [59,60].

Fig. 3 shows box plots of $PM_{2.5}$ and PM_{10} mass concentrations recorded in the two building pairs before and after relocation into the WELL-certified buildings. Additional statistics is presented in Table 3. The monitored $PM_{2.5}$ mass concentrations in all buildings were low, ranging from 1.9 μg/m^3 to 3.1 μg/m^3. The influences of building certification labels or seasons were not obvious. These results are in good compliance with the mean results reported in a modern office building in Finland (2.7–3.4 μg/m^3), but lower than the maximum values identified in the OFFICAIR study (for Hungary, mean $PM_{2.5}$ was in the range 9.7–32 μg/m^3) [45]. Other studies reported the mean $PM_{2.5}$ mass concentration of 15 μg/m^3 in Belgian offices [63] and 34.5 μg/m^3 in offices in Paris [64]. These studies were performed by means of gravimetric analysis with particle collection on a filter, unlike our study which relied on several assumptions for particle number to mass conversion.

Considering PM_{10} mass, the mean levels spanned from 6.5 μg/m^3 to 15.2 μg/m^3, with slightly lower levels reported in the WELL-certified buildings relative to BREEAM and conventional buildings. These levels are substantially lower than typical concentrations reported in other building types, such as schools (median = 102 μg/m^3) and homes (median = 34.7 μg/m^3) [65], and slightly lower than levels reported in other offices (mean = 20 μg/m^3) [63]. The main source of the PM_{10} mass concentrations were building occupants, almost exclusively within the coarse (2.5–10 μm) particle size fraction. This is evident from the comparison in PM_{10} mass concentrations during occupied and unoccupied hours; the PM_{10} levels during occupied hours of Company A averaged across all three campaigns at 12.4 μg/m^3 which was substantially higher than 4.2 μg/m^3 recorded during unoccupied hours. In Company B, this difference was comparably high (7.5 μg/m^3 vs 4.2

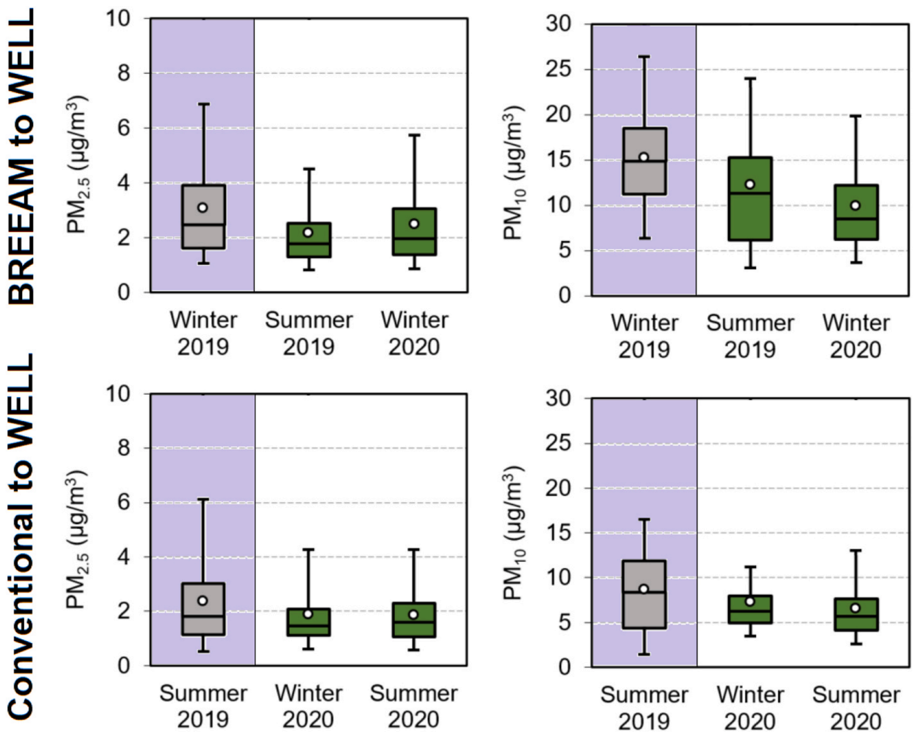

Fig. 3. Boxplots of particle mass concentrations ($PM_{2.5}$ and PM_{10}) before and after relocation into the two WELL-certified office buildings. The results are averaged across three measurement locations (open space, private office and meeting room). Shaded purple areas represent pre-relocation conditions, either from BREEAM (Company A) or from conventional building (Company B). The results are obtained based on 5-min mean concentrations. Box plots indicate 1st quartile, mean (while circles), median and 3rd quartile values. The ends of the whiskers represent 5th and 95th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

µg/m^3). Differences between occupied and unoccupied hours were not discernible for smaller particles ($PM_{2.5}$), indicating that large particle concentrations are dominated by occupancy, whereas small particles are governed by outdoor air. Similar findings are published for other indoor environments [66,67].

Comparison of the recorded $PM_{2.5}$ and PM_{10} mass concentrations against the standard values reveals that both building pairs were below the recommended ambient annual mean limits of WHO AQG for $PM_{2.5}$ (10 µg/m^3) and PM_{10} (20 µg/m^3), and below the recommended 24-h mean limits for $PM_{2.5}$ (25 µg/m^3) and PM_{10} (50 µg/m^3) [68]. It should however be noted that these guidelines pertain to outdoor air, and outdoor particles can differ in composition and morphology relative to those indoors [68]. At present, there is insufficient scientific evidence for establishing limits for indoor particle mass concentrations [69]. The

Table 4
Mean and standard deviation of concentrations of sulphur dioxide, ozone, nitrogen dioxide, TVOC, aldehydes and the most abundant individual VOC (µg/m^3 as toluene equivalent or using compound specific response factors), recorded in the two companies before and after their relocation into WELL buildings. The results are averaged across three measurement locations (open space, private office and meeting room). All values as expressed in µg/m^3.

Air pollutant	Company A	Company A	Company A	Company B	Company B	Company B
	BREEAM Winter 2019	WELL Summer 2019	WELL Winter 2020	Conventional Summer 2019	WELL Winter 2020	WELL Summer 2020
Sulphur dioxide	<0.7	<0.7	<0.7	<0.7	<0.7	<0.7
Ozone	<7	11 ± 3	<7	13 ± 1	<7	9 ± 2
Nitrogen dioxide	27 ± 2	19 ± 2	25 ± 0.5	20 ± 0.8	29 ± 3	17 ± 3
TVOC	88 ± 33	316 ± 123	325 ± 34	52 ± 12	760 ± 218	304 ± 47
Benzene	1.5 ± 0.3	<0.5	2.7 ± 0.4	<0.5	2.4 ± 0.2	<0.5
Toluene	6.3 ± 2.2	5.4 ± 1.1	7.0 ± 0.7	1.58 ± 0.04	5.5 ± 1.2	4.1 ± 0.5
Ethylbenzene	0.9 ± 0.1	2.1 ± 0.2	2.2 ± 0.1	0.50 ± 0.03	13 ± 4	5.1 ± 2.1
Xylenes	6.3 ± 1.1	10.2 ± 1.9	10.5 ± 0.2	2.0 ± 0.1	106 ± 36	44 ± 19
a-Pinene	0.8 ± 0.4	5.2 ± 0.4	3.9 ± 0.2	<0.5	4.6 ± 1.9	3 ± 2
3-Carene	<0.5	1.4 ± 0.3	0.8 ± 0.1	<0.5	0.8 ± 0.2	<0.5
Limonene	3.2 ± 0.1	5.1 ± 1.3	13 ± 2	<0.5	16 ± 5	4 ± 2
Hexanal	<0.5	9.4 ± 1.2	4.4 ± 1.0	0.9 ± 0.3	3.5 ± 0.7	3.0 ± 1.3
Nonanal	3 ± 2	6 ± 1	6 ± 3	2.4 ± 0.5	8 ± 2	15 ± 1
Decanal	4 ± 3	3.6 ± 0.3	8.0 ± 0.1	2.5 ± 0.2	<0.5	3.4 ± 0.8
Cyclotetrasiloxane, octamethyl-	12 ± 3	13 ± 7	11 ± 2	0.9 ± 0.1	14 ± 8	12 ± 2
Cyclopentasiloxane, decamethyl-	<0.5	<0.5	5.5 ± 0.7	0.7 ± 0.5	13 ± 7	4.9 ± 0.6
Ethanol, 2-butoxy-	<0.5	2.4 ± 1.4	2.9 ± 0.8	<0.5	<0.5	2.0 ± 0.7
Ethanol, 1-(2-butoxyethoxy)-	<0.5	16 ± 10	14 ± 2	<0.5	<0.5	<0.5
Ethanol, 2-(2-butoxyethoxy)-, acetate	<0.5	98 ± 74	30 ± 8	0.6 ± 0.5	<0.5	<0.5
2-Butanone, oxime	<0.5	<0.5	<0.5	<0.5	322 ± 223	<0.5
1-Butanol	1.3 ± 0.5	4.8 ± 1.0	1.5 ± 0.6	1.2 ± 0.1	5 ± 2	3 ± 1
2-Ethylhexanol	5 ± 2	4.7 ± 1.4	6.5 ± 0.3	2.1 ± 0.3	14 ± 1	14 ± 2
Formaldehyde	7.5 ± 0.2	17 ± 3	15 ± 0.9	15 ± 5	3.9 ± 2	15 ± 4
Acetaldehyde	3.2 ± 0.5	7.9 ± 0.7	6.9 ± 0.3	3.8 ± 0.5	2.3 ± 0.7	5 ± 2

95th percentile PM_{10} values in both BREEAM and WELL-certified buildings were ~25 μg/m^3. The mean PM_{10} results suggest that both WELL-certified buildings would generally comply with the enhanced thresholds for particulate matter of the WELL v2 (Feature 05 "Enhanced Air Quality": $PM_{2.5}$ = 10 μg/m^3 or lower; PM_{10} = 20 μg/m^3 or lower). However, the WELL v2 guideline does not specify duration of compliance, meaning that if the building performance verification would take place during the 5% of the time when the PM_{10} levels were higher (~25 μg/m^3), the building would not meet the requirements.

3.2. Summary of time-integrated air pollution data

The results from the time-integrated measurements are presented in Table 4. The inorganic air pollutants sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3) typically origin from outdoor combustion sources and photochemical reactions and are brought indoors by ventilation and infiltration. SO_2 in indoor air could not be detected in concentrations above the LOD (0.7 μg/m^3) throughout the study, whereas outdoors concentrations were low — 0.82 μg/m^3 during the campaign in summer 2019. Indoor O_3 was detected at levels above the LOD (7 μg/m^3) only during the summer measurements, and it ranged between 9 μg/m^3 and 13 μg/m^3. These values were well below the WHO and WELL maximum thresholds of 100 μg/m^3 often used as general guideline for IAQ (WELL v2, 2021; WHO, 2005). Indoor-to-outdoor (I/O) ratios for ozone were 0.22 (summer 2019) and 0.25 (summer 2020). The I/O ratio for ozone is most often in the range of 0.2–0.7 with the lower values in buildings with low air change rate (ACR) [70]. The outdoor concentrations and I/O ratios of inorganic gases are shown in Table S3 in Supplementary Information.

NO_2 was detected in indoor air of the offices both before and after the relocation, in concentrations above the LOD (0.7 μg/m^3) (Table 4 and Fig. 4). The maximum recorded concentration was 29 μg/m^3 in the WELL-certified building of Company B. This means that all buildings were always below WELL and WHO guideline values of <40 μg/m^3 [42, 71]. The NO_2 I/O ratio mainly depends on sources, season and ACR. The seasonal variation was observed in this study, with consistently higher values in the winter campaigns. In cases of the absence of indoor sources of NO_2 such as in typical office buildings with mechanical ventilation, the reported I/O ratio is 0.96 ± 0.39 (mean ± standard deviation) [72]. In our study, the I/O NO_2 ratios ranged between 0.51 and 0.90, and averaged across all buildings at 0.74 ± 0.14, which agrees with the typical interval of I/O ratios in offices.

As shown in Table 4, before the relocation to the WELL-certified buildings the average concentration of TVOC were low in both Company A (88 μg/m^3) and Company B (52 μg/m^3). These levels were well below the guideline values for indoor environments of 300 μg/m^3 specified by BREEAM [73] and the German Committee on Indoor Guide Values [74]. These values were similar to TVOC concentrations measured in 176 modern, urban office buildings in subarctic climate of Finland [75]; the geometric mean concentrations were 88 μg/m^3 in office rooms and 75 μg/m^3 in the open plan offices. In our study, the average TVOC concentrations significantly increased after the relocations to WELL buildings: in Company A to 316 μg/m^3 in summer and 325 μg/m^3 in the following winter; the values slightly above the referenced threshold (300 μg/m^3). In Company B after the relocation, the mean TVOC concentration was 760 μg/m^3 in the winter but it decreased to 304 μg/m^3 in the following summer. Therefore, shortly after the relocation, the TVOC levels were above the TVOC threshold of 500 μg/m^3 specified by WELL [42]. As similarly reported elsewhere, the concentration of most VOC decreases substantially in newly constructed buildings with mechanical ventilation within the first 6 months [76].

The average concentration of formaldehyde (Table 4 and Fig. 4) before the relocation was well below the guideline value of 100 μg/m^3 in the offices of Company A (7.5 μg/m^3) and Company B (15 μg/m^3); the same guideline values applies for general indoor environments [71] and BREEAM [73]. After the relocation to WELL-certified buildings, the concentrations in the offices of Company A were 17 μg/m^3 in summer and 15 μg/m^3 in winter, and in the Company B, they were 4 μg/m^3 and 15 μg/m^3 in winter and summer, respectively. These measured concentrations were below the WELL-compulsory guideline level for formaldehyde of 50 μg/m^3 but above the enhanced formaldehyde threshold of 9 μg/m^3.

Two large-scale studies report concentrations of VOC, formaldehyde and acetaldehyde in European office buildings that can serve as an indicator of typical exposure values: AIRMEX [77] and OFFICAIR [45]. However, both the AIRMEX study (from 2003 to 2008) and the OFFICAIR study (from 2012 to 2013) did not work with the concept of TVOC as they measured only individual VOC, formaldehyde and acetaldehyde (n = 23 in AIRMEX; n = 12 in OFFICEAIR). In both studies, the reported indoor concentrations of formaldehyde were generally lower in winter and higher in summer, and it was the opposite for the concentrations of VOC. The levels of acetaldehyde from our study are also within the range of those observed in the AIRMEX and OFFICEAIR studies. The observations from this study are in agreement with the published results. We report the individual VOC from this study (Table 4) that were commonly detected in the two building pairs. The concentrations were similar to those reported in the AIRMEX and OFFICAIR studies. Concerning specific sources, the BTEX compounds are associated with car exhaust; terpenes come from wood and fragrances; hexanal, nonanal and decanal have been identified as emissions associated with building materials and

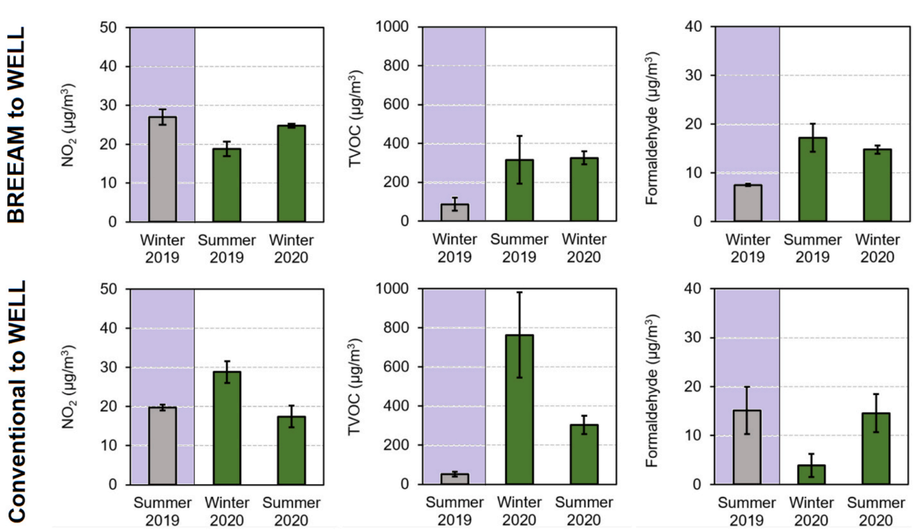

Fig. 4. Time-integrated concentrations and standard deviations of nitrogen dioxide (NO_2), total volatile organic compounds (TVOC) and formaldehyde before and after relocation into the two WELL-certified office buildings. The results are averaged across three measurement locations (open space, private office and meeting room). Shaded purple areas represent pre-relocation conditions, either from BREEAM (Company A) or from conventional building (Company B). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

humans (from skin); the cyclosiloxanes D4 and D5 are widely used in cosmetics and skin care products; 1-butanol and 2-ethylhexanol are often reported as products of alkaline degradation of phthalates; and acetaldehyde has sources in building materials and consumer goods. Fig. S1 summarizes the percentage contribution of various VOC categories to TVOC in the two building pairs.

Glycol ethers (2-butoxyethanol, 1-(2-butoxyethoxy) ethanol, 1-(2-butoxyethoxy) ethanol acetate) that are used as solvents in paints and cleaners were found in significantly higher concentrations in the Company A after relocation to the WELL-certified building. Xylenes also found in higher concentrations in both WELL-certified buildings are parts of paint thinners. 2-Butanone oxime, an anti-skinning agent in the formulation of alkyd paints, primers, varnishes and stain, was the single individual VOC identified in alarmingly high concentration in the WELL-certified building of Company B (322 μg/m^3, winter). This concentration exceeds the German Committee on Indoor Guide Values [74] threshold of 60 μg/m^3 by 5.4 times. This specific guideline value represents the concentration of a substance which, if reached or exceeded, requires immediate action as this concentration could pose a health hazard. The off-gassing process led to reduced concentrations to a level below LOD (<0.5 μg/m^3) during the 7–8 months between the winter measurement and the following measurement in summer.

3.3. Indoor air quality and thermal comfort survey data

Fig. 5 compares the mean, median, 1st and 3rd quartile satisfaction scores with IAQ and temperature before and after relocation to WELL-certified buildings. Table 5 summarizes the difference of means and statistical significance values before and after relocation. The results are displayed for the same seasons only (Company A, winters; Company B, summers). There was no statistically significant difference in satisfaction with IAQ and temperature obtained through two surveys after the relocation (no time and season effects), hence, those results are not presented.

Concerning temperature, occupants of Company A were generally neutral-to-slightly satisfied with this parameter. There was no statistically significant difference in satisfaction with temperature between BREEAM and WELL-certified buildings (p = 0.122). The results correspond to the physical measurements of air temperature and relative humidity which differed minimally between the two companies (Table 3). These satisfaction scores correspond to those reported in other BREEAM- [78] and LEED-certified buildings [27]. In Company B, temperature satisfaction in WELL-certified building was similar (neutral-to-slightly satisfied); however, the results were significantly improved relative to those obtained in the conventional building (p = 0.004; rho = 0.31). These results are intuitive, as the mean temperature was 22.5 °C in the WELL building, and 24.7 °C in the conventional building. The air temperature and temperature satisfaction results in the two building pairs also closely matched the results of occupants' thermal sensation, as shown in Fig. S2 and Table S4. Sources of occupant dissatisfaction with temperature in both building pairs are summarized in Fig. S3.

Table 5
Mean and standard deviation results of occupant satisfaction with IAQ and temperature before and after relocation into WELL buildings. The table also includes values for the difference or means (Δmean), significance (p-value) and effect size (Spearman's rho).

Company A	BREEAM	WELL			
	mean ± sd	mean ± sd	Δmean	p-value	Spearman's rho
Indoor air quality	0.44 ± 1.43	1.15 ± 1.42	0.71[a]	0.000	0.27
Temperature	0.28 ± 1.51	0.50 ± 1.53	0.23	0.122	0.08
Company B	Conventional mean ± sd	WELL mean ± sd	Δmean	p-value	Spearman's rho
Indoor air quality	−0.06 ± 1.50	1.50 ± 1.32	1.56[a]	0.000	0.48
Temperature	−0.42 ± 1.60	0.69 ± 1.77	1.11[a]	0.004	0.31

[a] The statistical significance (bolded rows) was considered when the p-value is below 0.05 and when the effect size (Spearman's rho) is above 0.2.

In both companies, occupant satisfaction with the IAQ was significantly higher in WELL-certified buildings (Fig. 5, Table 5). The mean difference in satisfaction scores was higher when transitioning from the conventional to WELL building — 0.71 for Company A (BREEAM to WELL) and as high as 1.56 for Company B (conventional to WELL). In conventional building, the satisfaction with air quality was perceived as neutral-to-slightly dissatisfying. Typical sources of dissatisfaction included tobacco smoke, other people and office materials (Fig. S4). In both building pairs, occupants who reported dissatisfaction with IAQ were further asked if air is stuffy or stale, smells bad from odors and is not clean; about 50% of dissatisfied occupants reported such experiences (Fig. S5).

The satisfaction scores with IAQ in WELL-certified buildings improved despite substantially higher concentration of TVOC and certain VOC. Individual VOC found at substantially higher levels in WELL building of Company B were xylenes, 2-butoxy ethanol, 1-(2-butoxyethoxy) ethanol, 2-(2-butoxyethoxy) ethanol acetate and -butanone oxime. Concentrations of hexanal and nonanal in the WELL-building were above odor thresholds of 1.4 μg/m^3 and 3.1 μg/m^3, respectively [79]. However, these compounds were unlikely to affect the perception of IAQ. Odor thresholds for e.g. xylenes, 1-butanol and 2-ethyl hexanol are in order of hundreds of μg/m^3 [80], so the detected levels of compounds could not have contributed to dissatisfaction with the IAQ even if it was the case.

The disagreement between measured concentrations of indoor air pollutants and perception of IAQ tends to be common, as evidenced by other studies [81,82]. In our study, the increased satisfaction scores with IAQ can be attributed in part to air temperature and relative humidity. IAQ and thermal comfort are strongly linked to one another, and they merit joint evaluation. For example, elevated air temperature and relative humidity are associated to negative perception of IAQ [83], which

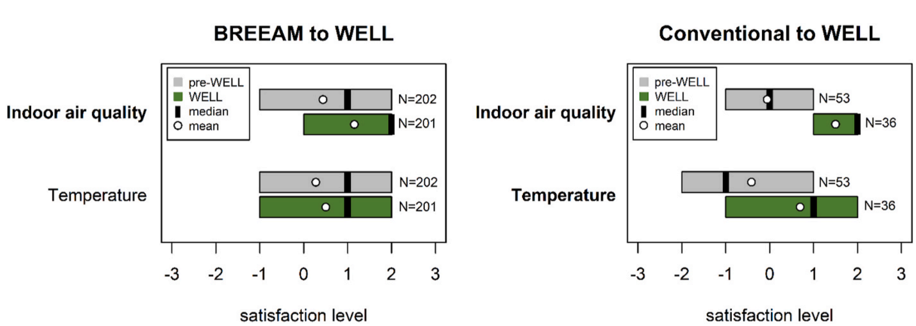

Fig. 5. Comparison of occupant satisfaction scores with IAQ and temperature in the pre-WELL and WELL-certified buildings of Companies A (BREEAM to WELL) and B (conventional to WELL). The comparisons were performed for the same seasons: Company A in winters; Company B in summers. "Newcomers" (new employees) were excluded from the analysis. Boxplots show 25th and 75th percentiles, mean (while circles) and median values for each parameter; omitting the outliers and minimum and maximum values due to the ordinal and limited ranged data between −3 and 3.

can explain significantly lower satisfaction scores with IAQ in conventional building of Company B. Nonetheless, in Company A, there was no statistically significant difference in objective and subjective measures of temperature between the two buildings. As explained by Hedge et al. [22], other possible "interferences" of green building design could result in improved occupant satisfaction with IAQ. Being aware of WELL-certification could have led to "positive bias" in occupants' satisfaction votes [84]. Additionally, "halo effect" that increases tendency of occupants for positive impressions is commonly reported, although we did not observe any significant differences by comparing the survey results from two post-relocation datasets. Other aspects of the indoor environment that we did not measure [85] as well as various non-measurable aspects of green-certification could have contributed to improved satisfaction scores.

3.4. Study strengths and limitations

The uniqueness of the study comes from the ability to measure diverse air pollutants in two companies – before and after their relocation into WELL-certified buildings. In addition, this study is among a few to include a direct comparison between physical and subjective measurements of IAQ before and after relocation into green-certified buildings, and the first one to do so in WELL-certified buildings and following the same cohort of the occupants. As such, this study can inform the green building certification developers as it offers direct benchmarking of IAQ levels and occupant satisfaction scores against the sample of green-certified and conventional buildings.

This study also contains several limitations. The number of examined case study buildings is small which limits the ability to assess their representativeness among the existing stock of green-certified buildings. We were also unable to obtain more comprehensive information about building systems and the list of credits met by the two WELL projects, which would be useful for further interpreting the physical and subjective results. Concerning physical measurements of IAQ, the following limitations are evident: 1) 1-month measurements during summer and winter seasons cannot be considered representative of the yearlong exposures; 2) particle mass results are limited to several assumptions made for the purpose of number-to-mass conversion; 3) time-integrated samples may not be representative of long-term exposures as they were based on limited number of 7-days continuous sampling campaigns which includes the unoccupied office hours. It should also be noted that despite the requirements of WELL v2 for building recertification every three years, the presented results may not be fully representative of the building lifetime operational performance.

Considering subjective results, limitations are the following: 1) the employees of the two companies were aware of this study and of the building certification labels, which could have led to bias in their perception and "halo effect" [86], although our results point towards the absence of this effect; 2) lack of agreement between subjective and physical data could be caused by other environmental factors which were not reported; 3) the percentage of survey respondents was high, but the absolute number of responses per campaign (~250) should be higher for better representativeness with a higher statistical power.

4. Conclusions

This study is the first attempt to understand the performance of WELL-certified office buildings by combining the field monitoring of IAQ and its subjective assessment. This was done by tracking the same cohort of employees who transitioned from two non-WELL buildings (BREEAM-certified and conventional) to two WELL-certified buildings.

Findings from the physical measurements suggest that regardless of the certification status and type, all buildings maintained similarly low concentrations of common air pollutants ($PM_{2.5}$, PM_{10}, CO_2, NO_2, SO_2 and O_3). For each of these air pollutants, compliance with various international standards was achieved and the influence of green certification labels was not obvious. However, higher concentrations of TVOC and several individual organic compounds were detected in WELL buildings which exceeded the upper recommended standard thresholds. Some of these compounds are relevant to human health, but currently are not embedded in the WELL certification program. For the majority of VOC in WELL buildings, concentrations decreased within 7–8 months after the relocation, including for TVOC (from 760 to 304 $\mu g/m^3$), indicating the process of chemical off-gassing from indoor materials, particularly from solvents in paints. These findings indicate the need for obligatory adoption of low-emission materials that can mitigate the VOC exposures in the early lifetime of WELL buildings. Concerning thermal environment, air temperatures were kept within recommended ranges both in BREEAM and WELL buildings, and were elevated in the non-certified (conventional) building (24.7 °C). The relative humidity was generally below 60%, except in one WELL building where the humidity was 73% during 5% of the occupied hours.

Pre- and post-relocation surveys indicated that occupants of BREEAM and WELL buildings had similar levels of satisfaction with thermal environments. Statistically significant improvements in temperature satisfaction and thermal sensation were detected after relocation from conventional to WELL-certified building; these results were well correlated with the air temperature data. Concerning IAQ, occupants were significantly more satisfied with IAQ in WELL-certified buildings than those in BREEAM and conventional buildings. Notably, the improvement of satisfaction scores were higher when relocating from the conventional building, relative to relocating from the BREEAM building. Based on these results it can be concluded that occupants of WELL-certified buildings were more satisfied with IAQ, although the physical measures of IAQ were equal or even lower. This outcome may be explained in part by influences of other environmental factors, primarily thermal comfort. These results may also suggest that the impact of WELL certification on occupant satisfaction could extend beyond the measurable IAQ parameters, which is the subject that merits further attention.

While the green building industry has a long-standing history of attention to human health, there has been a recent shift in the prioritization of this issue relative to the others, with a new emphasis on features that explicitly promote the experience of building occupants. In this context, the WELL certification is the new and emerging rating system that aims to promote health-based building design and operation. Our results suggest that working in WELL-certified buildings leads to improved satisfaction scores with IAQ, but this data were not supported with the result of physical measurements of IAQ. The current requirements of WELL-certification scheme include selected air pollutants intended to protect occupants' health. Our results point towards the need for inclusion of a broader suite of VOC, along with the requirements for compliance with surveys evaluating people's perception and satisfaction with IAQ.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.108182.

Authors contributions

Dusan Licina: Conceptualization (lead); Formal analysis (lead); Funding Acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (lead); Writing-original draft (lead); Writing-review & editing (lead). Sarka Langer: Formal analysis (equal); Investigation (supporting); Methodology (supporting); Writing-original draft (equal); Writing-review & editing (supporting).

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